



## A JOINT ISI-CANCELLING AND MATCHED FILTER

## ADAPTIVE DIGITAL EQUALIZER

## TECHNICAL FIELD OF THE INVENTION

This invention relates to digital equalizer technology and more particularly to fractional-spaced equalizers that are preceded by a MF.

## BACKGROUND OF THE INVENTION

In terms of suppressing out-of-band distortion and canceling multi-path ISI, the standard design of most digital receivers cascades a MF with an adaptive equalizer. The MF usually takes the form of a square-root raised cosine (RRC) response in order to maximize SNR while the adaptive equalizer often operates as a fractional-spaced equalizer (FSE) to allow inverse modeling of the propagation channel across the full spectral band, as apposed to only at pass-band frequencies in the symbol-spaced equalizer.

In modern receivers the transmitter's pulse-shaping process re-proportions the spectral energy of the base-band signal such that the major spectral components occupy the low-frequency band while the minor spectral lobes are made to occupy the high frequency band. The band-limited representation of the transmitted signal infers that channel inversion at out-of-band frequencies is only as important to restoring full-received SNR as to the extent that the signal's high frequency spectral components are important to representing the distortion-less transmitted modulation.

In terms of suppressing such out-of-band distortion signals as CW jamming the FSE has historically relied upon both the recursion of its ISI-canceling operation and on the out-of-band

attenuation characteristics of the MF preceding it. If the source of the distortion is thermal noise, however, the FSE must rely exclusively on the MF as the equalizer's spectral side-lobe levels are not well defined, are susceptible to variations in the adaptation constant, and therefore, cannot suppress the noise prior to decimation of the signal to the symbol rate.

With the importance of multi-path ISI cancellation relatively unimportant at out-of-band frequencies and with the pre-FSE RRC MF providing suppression of out-of-band interference, the responsibilities of the FSE's out-of-band mask have remained limited to the cancellation of excess adjacent channel interference not suppressed by the MF. It is noted that both the pre-FSE RRC MF and FSE are digital filters that operate at the same sample rate and whose responsibilities across the frequency band are approximately decoupled. Because of this, both filters can be combined into a single filter if control over the FSE's spectral mask can sustain well-defined side-lobes that are immune to changes in the equalizer's adaptation constant.

This suggests a single filter implementation for the cascade design. From the point of hardware, a cascading of successive digital filters demands that separate bank of FPGA multipliers must be used to service the demands of each filter in the cascade chain. A single filter implementation of the traditional RRC MF plus FSE cascade design reduces cost as similar hardware components can be used to service the processing of associated with each. Although an increase in computational complexity must result when two separate processes are combined to conserve hardware, many options present themselves to minimize this increase. Consequently, reductions in both computational complexity and power consumption over that required for the traditional cascade design are possible.

Accordingly, it is one objective of the present invention to provide a FSE that can simultaneously affect control over the equalizer's pass-band, roll-off, and side-lobe characteristics using a technique of constrained optimization so as to form a joint ISI-cancelling

and MF update that can achieve the received SNR performance of the state-of-the-art cascade pre-FSE RRC MF plus FSE design.

It is another object of the present invention to provide a FSE that implements a time-multiplexing architecture that enables a single bank of multiplier elements to perform the inner product computations associated with both the ISI-canceling and MF updates within the confines of a constrained optimization update, the purpose to provide for reduced hardware complexity over that of the state-of-the-art cascade pre-FSE RRC MF plus FSE design.

It is the further object of the present invention to provide a FSE that operates as a joint ISI-canceling and MF FSE where the error associated with ISI-cancellation may be derived from any number of existing algorithms within the confines of the constrained optimization update of the present invention.

It is the further object of the present invention to interject the process of time-domain windowing of the constraint waveform into the constrained optimization update so as to minimize the increase in computational complexity incurred from the introduction of the time-multiplexing architecture.

It is the further object of the present invention to provide a FSE operating as a joint ISI-canceling and MF FSE where the rate at which the equalizer's weights are updated in accordance with the MF processing is controlled via an algorithm to minimize computational workload.

It is the further object of the present invention to provide a FSE operating as a joint ISI-canceling and MF adaptive equalizer which implements an initialization of the equalizer's FF weights using a selected set of coefficients of an RRC MF, the intent of which is to reduce the acquisition time of the MF characteristics of the FSE's steady-state joint inverse channel and MF function.

It is the further object of the present invention to provide a FSE operating as a joint and MF FSE under a constrained optimization update when the FSE is partitioned as a poly-phase process.

#### SUMMARY OF THE INVENTION

These and other problems have been solved by combining the pre-FSE RRC MF and the FSE into a single filter joint process FSE that controls the spectral side-lobe behavior of the equalizer while simultaneously maintaining control over the equalizer's spectral pass-band and roll-off characteristics in accordance with the criterion for cancellation of ISI.

To accomplish this, the gradient descent algorithm of the standard unconstrained FSE, which is responsible for driving the ISI-cancellation process, was modified to incorporate a constraint via the Lagrange multiplier technique. The constraint is defined to be a restriction that the equalizer's weights be orthogonal to a waveform whose major spectral components reside at out-of-band frequencies. If the FSE is operated as a base-band equalizer then out-of-band refers to the high frequency band, and if FSE is operated as a band-pass equalizer, out-of-band refers to that portion of the frequency band not occupied by the signal's major spectral components.

To generate the orthogonality between the equalizer's weights and the out-of-band signal the inner product of these two time sequences is computed and subtracted from a desired orthogonality target on an iteration-by-iteration basis. The difference is scaled and then used to update the equalizer's weights in a direction so as to minimize the error. The orthogonality target is a scalar  $\beta$  of value less than 1.0 which forces the recursion of the constraint update to generate a low-pass process of the FSE at out-of-band frequencies. As a result, the spectral side-lobe development of the FSE is controlled so as to generate a low-pass process. The error between the measured orthogonality and targeted orthogonality is termed the constraint error and the high

frequency signal is termed the constraint waveform.

Thus, the modified FSE updates the equalizer's weights twice per equalizer iteration - once in accordance with the minimization of the mean-squared error associated with ISI cancellation and the second time in accordance with the criterion for the added constraint. The modified equalizer is termed the joint ISI-canceling and MF adaptive equalizer, and because of the development of well-defined spectral side-lobes at steady-state, this joint process equalizer provides for robust RRC MF processing as well as simultaneous channel inversion.

The primary technical advantage of the present invention is that from the configuration of the linearly constrained algorithm driving joint process equalizer a time-multiplexing architecture is employed to allow a single bank of multiplier elements to service two inner product computations, that associated with the ISI cancellation and that associated with the added constraint for the MF processing. A single bank of multipliers servicing the needs of both ISI cancellation and MF processing contrasts with the two separate banks of multipliers required in the traditional cascade design, and therefore, the present invention conserves hardware in the system design.

The present invention pertains to the creation of a joint ISI-canceling and MF process for any FSE that is sampled at more than 1-sample-per-symbol and satisfies the Nyquist criterion. Although a FSE that is sampled exactly at the Nyquist rate can sufficiently perform full band channel inversion, FSEs are often sampled above the Nyquist rate at 2-samples-per-symbol (or twice the transmitted symbol rate) in order to simplify the subsequent task of down-sampling to the symbol rate. Hence, a preferred embodiment of the present invention is designed to operate the constrained FSE at twice the symbol rate. In this case, the decimation device at the output of the equalizer takes the form of a 2:1 commutator.

The time-multiplexing structure of the present invention remains unchanged regardless of the

choice of the preferred embodiment for the FSE's sampling rate. For example, the constrained joint ISI-canceling and MF FSE operating at 2-samples-per-symbol performs a time-share of a single bank of multiplier elements with the samples of the two sequences accessing the multiplier bank, either the input data and the equalizer's weights or the equalizer's weights and the constraint waveform, separated in time at half-intervals of the transmitted symbol rate, or  $T_{sym}/2$ . In an alternate embodiment, the joint ISI-canceling and MF FSE can be sampled at less than 2-samples-per-symbol if the Nyquist criterion is satisfied. Here, the time-multiplexing scheme is still based upon a time-share of a single bank of multiplier elements, but now with the samples of the two sequences accessing the multiplier bank separated in time at fractional intervals less than  $T_{sym}/2$ . Thus, although the number of multiplier elements contained within the single bank increases as the FSE is sampled at larger rates, the time-multiplexing architecture of the present invention still provides for a conservation of hardware.

As previously mentioned, the constrained update of the present invention works in conjunction with an update responsible for inversion of the propagation channel. Amongst the various existing configurations for the algorithm that generates the error associated with channel inversion the constrained update of present invention is generally used with, but is not exclusive to, three different channel inversion updates: a training sequence update, a decision-based update, and a statistically based update. Used in conjunction with the newly formed linearly constrained algorithm, these three updates, as well as others not mentioned here, form embodiments of the present invention.

In the training sequence embodiment the error associated with ISI-cancellation is formed from the difference between the equalized signal and a known training sequence. In an alternate embodiment, a decision device, or slicer, forms the error as the difference between the equalized signal and the slicer's output, which is a quantized version of equalized signal. A third

embodiment of the present invention forms this error as the scaled difference between the power of the equalized signal and a parameter describing the statistical properties of the original transmitted modulated signal.

A decision-directed configuration for the channel inversion error algorithm is often used in conjunction with a decision-feedback update for robust cancellation of ISI. Hence, a preferred embodiment of the present invention uses the joint ISI-canceling and MF linearly constrained update within the configuration of a decision-feedback equalizer.

Another technical advantage of the present invention is that the joint ISI-canceling and MF constrained update can be applied to a FSE that is partitioned as a poly-phase process. The poly-phase decomposition of the standard FSE embeds the  $M:1$  decimator normally occurring at the output of the equalizer to within the FSE using the Noble Identity. As a result, the multiplier bank is partitioned into  $M$  multiplier sub-banks, each containing half the total multipliers of the non-partitioned multiplier bank. Although the workload per-output-point of the poly-phase partitioned FSE is greater than that of the non-poly-phase partitioned FSE by a factor of  $M$ , the poly-phase configuration commutates every  $M$ -th input sample of the distorted waveform to only one of the  $M$  sub-banks. Thus, the situation in the non-poly-phase FSE in which every input sample is processed by every equalizer weight is avoided in the poly-phase configured FSE. With regard to the present invention the linearly constrained poly-phase FSE is designed to form a joint ISI-canceling and MF process by computing  $M$  additional inner products associated with the constraint update. In the preferred embodiment of the present invention where  $M = 2$  the joint ISI-canceling and MF poly-phase FSE is able to conserve the hardware associated with the RRC MF's multiplier elements at the expense of four times the workload of the standard non-poly-phase configured unconstrained FSE.

A further technical advantage of the present invention is that when the constraint waveform

is defined as a frequency dependent sinusoid residing in the high frequency band, the linearly constrained update may be modified to determine the most minimal duty cycle of the sinusoid required to saturate performance. In this embodiment the time-series of the high frequency sinusoidal signal is time-domain windowed with a digital window function so as to render the samples farthest from the midpoint of the total duty cycle with negligible importance as compared to the most central samples. The net effect is that the samples of negligible amplitude need not contribute in the inner product computation associated with the constraint update. This reduces the computational complexity and improves power efficiency.

It has been determined that the constraint, windowed or not windowed, need not contribute an update of the equalizer's weights at all iterations. Thus, the joint process equalizer may be designed with a switch to control at which iterations an update of the equalizer's weights associated with the MF processing is to occur. This also results in a reduction in the number of computations and the operational power needed to run the joint process equalizer.

Since the equalizer's impulse response at steady-state is to be a composite of both the inverse channel model and RRC MF, initialization of the equalizer with the RRC MF taps attains half the final solution from the start. Hence, initialization reduces acquisition time of the MF characteristics, which allows the MF processing to be partially eliminated sooner in the update.

The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the joint ISI-canceling and MF adaptive equalizer that follows may be better understood. Additional features and advantages of this joint process equalizer will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that conception and the specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purpose of the present invention. It should also be realized



by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

**FIG. 1** is a high-level block diagram of a state-of-the-art MF plus FSE cascade system;

**FIG. 2** is a composite high-level/detailed block diagram of a state-of-the-art MF plus FSE cascade (non-poly-phase partitioned) system;

**FIG. 3** is a detailed block diagram of a preferred embodiment of the algorithm responsible for adjusting the error associated with channel inversion of the state-of-the-art MF plus FSE cascade system;

**FIG. 4** is a detailed block diagram of a preferred embodiment of the weight update algorithm of the state-of-the-art MF plus FSE cascade system;

**FIG. 5** is a high-level/detailed block diagram of the joint ISI-canceling and MF adaptive equalizer operating at 2-samples-per-symbol ( $M = 2$ ) in accordance with a preferred embodiment of the present invention;

**FIG. 6** is a detailed block diagram of the algorithm that generates samples of the constraint waveform in accordance with a preferred embodiment of the present invention;

**FIG. 7** is a detailed block diagram of the constraint error adjustment algorithm in accordance with a preferred embodiment of the present invention;

**FIG. 8** is a detailed block diagram of the rate control algorithm for the constraint update of

the equalizer weights in accordance with a preferred embodiment of the present invention;

**FIG. 9** is a detailed block diagram of the algorithm that generates the channel inversion error which utilizes a training sequence-based update in accordance with a preferred embodiment of the present invention;

**FIG. 10** is a detailed block diagram of the algorithm that generates channel inversion error which utilizes a decision-directed update in accordance with a preferred embodiment of the present invention;

**FIG. 11** is a detailed block diagram of the algorithm that generates the channel inversion error which utilizes a blind update via the constant modulus algorithm (CMA), in accordance with a preferred embodiment of the present invention;

**FIG. 12** is a detailed block diagram of the algorithm that calculates the modulus factor of the blind CMA update, in accordance with a preferred embodiment of the present invention;

**FIG. 13** is a detailed block diagram of the algorithm which performs a decision-feedback update of the joint ISI-canceling and MF equalizer in accordance with a preferred embodiment of the present invention;

**FIG. 14** is a detailed block diagram of the algorithm which performs a windowing of the constraint waveform using a single window function in accordance with a alternate embodiment of the present invention;

**FIG. 15** is a detailed block diagram of an of the algorithm which performs a windowing of the constraint waveform using a window derived from a composite of many window functions in accordance with an alternate embodiment of the present invention;

**FIG. 16** is a detailed block diagram of the algorithm that performs an initialization of the contents of the equalizer FF weight register bank using the pre-FSE RRC MF taps in accordance with a preferred embodiment of the present invention; and

**FIG. 17** is a detailed block diagram of the polyphase configuration of the joint ISI-canceling and MF adaptive equalizer in accordance with a preferred embodiment of the present invention.

#### DETAILED DESCRIPTION OF THE PRIOR ART

Before discussing the joint ISI-canceling and MF adaptive digital equalizer, it will be useful to discuss the state-of-the-art equalizer and MF cascade design.

There are no known joint ISI-canceling and MF adaptive digital equalizer configurations that permit control the spectral side-lobes of the FSE so as to generate a RRC MF state across the full spectral band of the equalizer, and so, the state-of-the-art is defined to be the design in **FIG. 1**, an RRC MF **101** cascaded with a FSE **102**.

**FIG. 2** depicts a detailed block diagram representation of **FIG. 2** showing the state of the art MF plus FSE cascade filter system operating at M-samples-per-symbol (M times the symbol rate).

The process is as follows. Samples of the distorted input waveform contained within a data register bank **201** associated with the RRC MF processing are shifted to the right by one register position. The sample of distorted waveform is input to the first (far left) position of the MF data register bank **201**. The contents of the MF data register bank **201** then engage the contents of an RRC MF weight register bank **202**, which stores the RRC MF coefficients, in an inner product computation using a bank of multiplier elements **203** and a bank of summation nodes **204**. This inner product IP represents a sample of the post-filtered pre-equalized signal.

Next, the contents of the equalizer data register bank **205**, storing the previous samples of the post-filtered and pre-equalized signal, is shifted to the right by one register position. The sample of the previously computed inner product IP is input to the first register position of the equalizer

data register bank **205**. The contents of the equalizer data register bank **205** then engage the contents of the equalizer weight register bank **206**, storing the current values of the equalizer's weights, in an inner product computation using a bank of multiplier elements **207** and a bank of summation nodes **208**. This inner product represents a sample of the equalized signal sampled at M-samples-per-symbol.

The equalized sample is then passed to a M:1 commutator **209** which decimates the equalized signal to the symbol rate. The decimated signal is then passed to an algorithm ALG-ISI-ERR **210** that forms the error needed to drive the weights in accordance with criterion for ISI cancellation. Three different state-of-the-art configurations for ALG-ISI-ERR **210** are based upon a training sequence, a decision device, or a statistically based update. These configurations will be presented in detail during the description of the embodiments of the present invention.

Next, the error from ALG-ISI-ERR is delivered to an algorithm ALG-1 **211** that transforms the error into an adjustment signal used to update the equalizer's weights in accordance with the criterion for channel inversion. ALG-1 **211** refers to one of any number of algorithms that can transform the error into a signal capable of controlling the adaptation of the equalizer's weights.

One possible configuration for ALG-1 **211** is shown in **FIG. 3** and consists of a complex conjugation operator **301**, a scalar adaptation constant  $\mu$  **302**, and a multiplier **303**. The adaptation constant  $\mu$  **302** multiplies the ISI equalization error to form a product representing an adjustment signal for the weight update associated with the channel inversion process. The operating range for the adaptation constant  $\mu$  **302** is

$$0 < \mu < \mu_{\text{crit}} \quad [1]$$

where the critical value  $\mu_{\text{crit}}$  is inversely proportional to the energy of the samples of distorted signal contained with in the equalizer data register bank **201** (**ref. FIG. 2**) at the current iteration.

Continuing with the process flow of **FIG. 2**, the adjustment signal produced at the output of **ALG-1 211** is then delivered to an algorithm **ALG-2 212** which updates the contents of the equalizer weight register bank **206**. **ALG-2 212** refers to one of any number of algorithms that can make use of an adjustment signal to update the contents of the equalizer weight register bank **206**.

One possible configuration for **ALG-2 212** is shown in **FIG. 4**. The sample of adjustment signal formed from the output of **ALG-1 212** (ref. **FIG. 2**) multiplies the contents of the equalizer data register bank **205** (ref. **FIG. 2**) using a bank of multiplier elements **401**. The resulting bank of products is added to the current contents of the equalizer weight register bank **206** (ref. **FIG. 2**) using a bank of summing nodes **402**. The bank of sums produced is stored in the equalizer weight register bank **206** (ref. **FIG. 2**).

As a specific example of the equalizer's FF weight update, the contents of the first (far left) register of the equalizer data register bank **205** (ref. **FIG. 2**) multiplies the adjustment signal produced from **ALG-1 212** (ref. **FIG. 2**) using the first (far left) multiplier of the multiplier bank **401**. The product adds to the first (far left) register position of the equalizer weight register bank **206** (ref. **FIG. 2**) using first (far left) summing node of the bank of summing nodes **402** and the sum is stored in the first register position of the equalizer weight register bank **206** (ref. **FIG. 2**). The process continues with the updates associated with the next successive register positions of the equalizer weight register bank **206** (ref. **FIG. 2**).

Retuning to the processing in **FIG. 2**, after updating the contents of the equalizer weight register bank, the entire processing of the MF and FSE cascade system repeats with the contents of the MF data register bank **201** shifted to the right by one position to prepare for the next pre-filtered sample to be input.

## DETAILED DESCRIPTION OF THE INVENTION

**FIG. 5** depicts a detailed block diagram of the joint ISI-canceling and MF adaptive equalized in accordance with a preferred embodiment of the present invention. **FIG. 5** indicates the time-multiplexing architecture in which a single multiplier bank **504** is utilized to perform two separate inner product computations, that associated with the channel inversion update and that related to MF processing. In this embodiment the equalizer operates at 2-samples-per-symbol (twice the symbol rate  $M = 2$ );

Elements currently residing within a data register bank **501** are shifted to the right by one position. A sample of the distorted input waveform is then loaded into the first position of the data register bank **501**. At time  $t-1$ , after the current distorted sample enters the first data register position, switch **S1 502** is closed to allow the contents of the data register bank **501** to engage the contents of a second register bank **503**, storing values of the equalizer's feedforward (FF) weights, in an inner product using a bank of complex multiplier elements **504** and summation nodes **505**. This inner product represents the current sample estimate of the equalized signal. Samples of the equalized signal calculated from the previous inner product are then passed through a 2:1 commutator **506**, which discards every other sample to decimate to the symbol rate. The samples of decimated signal are then delivered to switch **S1 502**. Switch **S1 502** in this position prohibits the inner product samples associated with the MF processing from entering the signal processing chain associated with the channel inversion process. With switch **S1 502** closed, samples of the equalized signal are delivered to an algorithm **ALG-ISI-ERR 507** to form the error signal associated with the channel inversion update.

The error signal associated with the channel inversion is then delivered to an algorithm **ALG-1 508** that transforms the error into an adjustment signal used to update the equalizer's weights in

accordance with the criterion for channel inversion. ALG-1 508 refers to one of any number of algorithms that can control the adaptation of the equalizer's weights.

**FIG. 3** illustrates a detailed block diagram of ALG-1 508 in accordance with a preferred embodiment of the present invention as previously described and discussed.

Referencing **FIG 5**, the adjustment signal formed at the output of ALG-1 508 is then passed to switch S1 502. In this position, switch S1 502 permits an update of the equalizer's weights when the adjustment signal is derived from the channel inversion process and prevents the channel inversion error adjustment signal from updating the weights when the present invention switches its mode of operation to the MF processing. With switch S1 502 in a closed position, the adjustment signal derived from ALG-1 508 is delivered to algorithm ALG-2 509 which performs an update of the contents of the equalizer's FF weight register bank 503. ALG-2 509 refers to one of any number of algorithms that can control the adaptation of the equalizer's weights.

**FIG. 4** illustrates a detailed block diagram of ALG-2 509 in accordance with a preferred embodiment of the present invention as previously described and discussed.

This completes the ISI-cancellation process of the present invention for the current iteration.

Next, the MF processing is initiated. A third register bank 510 of the present invention stores samples of a signal defining samples of the constraint waveform. This waveform represents a signal whose major spectral components reside in the high frequency band and pertains to any function that can become uncorrelated with the equalizer's impulse response within the constrained optimization algorithm so as to transform the equalizer's spectral side-lobes into a robust spectral mask.

A preferred embodiment of the present invention defines the constraint waveform as a set of independent complex sinusoids, each residing above the quarter-sample rate. For example,

suppose the  $i$ -th constraint sinusoid in the set  $\{i = 1, 2, \dots, N\}$  is defined as

$$c_i(k) = A \exp\{j(2\pi f_i k + \phi_i)\} \quad [2]$$

The terms  $A$ ,  $f$ , and  $\phi$  refer to the constraint sinusoid's amplitude, frequency, and phase. The frequency changes with time (equalizer iteration  $n$ ) through index  $i$  so as to sweep out the entire out-of-band frequency band.

$$i = (n - 1)(\text{mod})N + 1 \quad [3]$$

The total number of independent sinusoids  $N$  is determined by trial and error tuning to maximize the full- received SNR. A preferred embodiment of the present invention spaces the complex tones at equidistant frequency intervals starting at the spectral nulls of the pre-FSE RRC MF and ending at the half-sampling rate.

Other embodiments may increment the frequency as in a ramping function or FM sweep (linear variation with iteration index  $n$ ), or higher order non-linear variations. The constraint waveform may also be defined to be a real sinusoid or a real cosinusoid. Sinusoidal amplitude  $A$  may take on any value above zero,  $A > 0$ , or may take on a time-varying format  $A(t)$  if desired. An arbitrary phase either random or deterministic  $\phi$  can be included or can be derived from many phases  $\phi$ . With respect to the constraint vector sinusoidal tap index  $k$  ranges from 1 to  $L$  where  $L$  is the number of equalizer coefficients.

Referring back to **FIG. 5**, after the contents of the equalizer FF weight register bank **503** have been updated using **ALG-2 509** in accordance with the criterion for channel inversion, samples of the signal representing the constraint waveform are loaded into the constraint register bank **510** using an algorithm **ALG-3 511**. **ALG-3 511** refers to one of any number of algorithms that can be used to define the contents of the constraint register bank **510**.



**Fig. 6** depicts a detailed block diagram of ALG-3 **511** in accordance with a preferred embodiment of the present invention. An index  $i$  is formed from an overflow counter **601** that cyclically counts between 1 and  $N$ , at the symbol rate, and indexes a register bank **602** storing the  $N$  out-of-band constraint frequencies. The overflow counter **601** is comprised of a scalar fixed to the value of 1 **603**, a register **604** to store the current state of the increment, an overflow test **605** to reset the value of the counter register **604** to 1 after the count exceeds the value set by a parameter  $N$  **606** which the overflow test **605** uses to conduct its comparison, and a summing node **607** to perform the incrementation of the counter register **604**.

At the conclusion of the ISI-cancellation update, overflow counter **601** increments index  $i$  to access the next frequency in the frequency array **602**. The selected frequency  $f_i$  is then passed to a sinusoidal generator **608** which generates samples of the complex sinusoid.

Referencing **FIG 5**, the samples of constraint waveform are then loaded into the constraint register bank **510**, but can also be passed first to an optional algorithm ALG-4 **512** when the constraint waveform is sinusoidal in nature to limit duty cycle as a means to reduce the computational complexity of the MF processing. The composition of ALG-4 **512** will be discussed later.

Since the samples of each sinusoid are known apriori to the equalization, the constraint waveform may be loaded from ROM. Thus, an alternate embodiment of the ALG-3 **511** and ALG-4 **512** combination is a ROM lookup table.

Continuing with the process flow in **FIG. 5**, at time  $t_2$ , shortly after time  $t_1$  and prior to the input of the next distorted sample to be processed, switch S1 **502** is opened and a second switch S2 **517** is closed to allow computation of a second inner product, this time between the contents of the constraint register bank **510** and the contents of the equalizer FF weight register bank **503**. Once again the bank of multiplier elements **504** and bank of summing nodes **505** are used in

forming the inner product. This inner product represents a measurement of the orthogonality between the equalizer's weights and the complex constraint sinusoid residing at frequency  $f_i$  at the current iteration.

The sample of the previous inner product between the equalizer's weights and the constraint waveform is then passed to the 2:1 commutator **506**, which discards every other sample. Switch S2 **517** is again encountered to deliver the orthogonality inner product to the subsequent algorithms involved in the MF processing. With switch S2 **517** closed the orthogonality inner product at the output of the 2:1 decimator **506** is subtracted from a parameter  $\beta$  **518**, termed the constraint level, using differencing node **519**. The constraint level  $\beta$  **518** defines the *targeted* strength of the orthogonality between the equalizer's weights and the constraint waveform. The operating range for  $\beta$  **518** is

$$0 \leq \beta < 1 \quad [4]$$

The difference, termed the constraint error, is passed to an algorithm ALG-5 **520** that controls the rate of acquisition of the constraint update. A preferred embodiment of the present invention sets  $\beta = 0$  to maximize the strength of the orthogonality built between the equalizer's weights and the constraint waveform. In turn, the differencing node **519** is not necessary and so is removed. ALG-5 **520** refers to any number of algorithms that can be used to dictate the rate of acquisition of the constraint update.

**FIG. 7** depicts a detailed block diagram of ALG-5 **520** in accordance with a preferred embodiment of the present invention. Samples of the MF constraint error are passed to a complex conjugation operator **701** and the result is scaled by a parameter  $\alpha$  **702**, equal to the inverse of the number of samples of the complex constraint sinusoid waveform multiplied by the amplitude of the complex constraint sinusoid, using a multiplier element **703**. When the constraint sinusoid is of unit amplitude the multiplicative parameter  $\alpha$  **703** reduces to  $1/L$ . The

scaled MF constraint error represents an adjustment signal for the equalizer weight update associated with the MF processing.

In **FIG. 5** the adjustment signal formed at the output of **ALG-5 520** is then passed to switch **S2 517**. In this position, switch **S2 517** permits an update of the contents of the equalizer's **FF** weight register bank **503** when the adjustment signal is derived from the MF constraint error and prevents the MF constraint error adjustment signal from updating the contents of the equalizer **FF** weight register bank **503** when the present invention switches its mode of operation to back to the channel inversion process.

With switch **S2 517** closed the adjustment signal derived from the MF constraint error is passed to an optional algorithm **ALG-6 521** to control the rate at which the contents of the equalizer weight register bank **503** are to be updated in accordance the criterion for the MF constraint. **ALG-6 521** refers to any number of algorithms that can be used to dictate the update rate of the equalizer's weights in accordance with the criterion for the constraint.

**FIG. 8** depicts illustrates **ALG-6 521** in accordance with a preferred embodiment of the present invention. The adjustment signal for the MF constraint update is passed to a switch **S3 801** whose open/closed state is controlled by an overflow counter **802**. The overflow counter **802** is comprised of a scalar fixed to the value of 1 **803**, a register **804** to store the current state of the increment, a summing node **805**, an overflow test **806**, switches **S4 807**, **S5 808** and **S6 809**, and three parameters, **P0 810**, **P1 811**, and **P1 812**, to dictate the maximum count of the overflow counter **802**.

As the joint ISI-canceling and MF adaptive equalizer initiates processing the overflow counter **802** counts at the symbol rate from 1 to the value set by parameter **P0 810** whose value is accessed by the overflow counter **802** through switch **S4 807** which, at initial conditions, is in a closed position. Through the duration of this count, switch **S3 801** is in a closed position to allow

the adjustment signal derived from the MF constraint error to update the contents of the equalizer FF weight register bank **503** (ref. FIG. 5). When the incremental count in the register **804** exceeds the value specified by P0 **810** the overflow test **806** results in a binary TRUE, and switches S3 **801** and S4 **807** are opened. Switch S4 **807** is then disabled from the processing and remains in an open state throughout the remainder of the joint ISI-canceling and MF update.

The increment register **804** is then set to zero and switch S5 **808** is closed to allow the overflow test **806** to use the value given by parameter P1 **811** as the new threshold of the maximum count. As the update of the joint process equalizer continues, the overflow counter **802** starts counting again from 1, but counts this time to the value given by P1 **811**. During this counting switch S3 **801** remains in an open position to keep the constraint update from updating the equalizer weights.

Switch S3 **801** remains in an open position until the value in the counter register **804** exceeds the value given by P1 **811** upon which the overflow test **806** results in a binary TRUE again which prompts switch S3 **801** to close to resume updates of the contents of the equalizer's FF weight register bank **503** (ref. FIG. 5) in accordance with the MF constraint criterion. At the same time that switch S3 **801** is closed, switch S5 **808** is opened and switch S6 **809** is closed to set the maximum count of the overflow counter **806** to the value given by P2 **812**.

The increment register **804** is again set to zero and as the update of the joint process equalizer continues, the overflow counter **802** starts counting again from 1 **803**, but counts this time to the value given by P2 **812**. During this counting switch S3 **801** remains in a closed position until the value in the counter register **804** exceeds the value given by P2 **812** upon which the overflow test **806** results in a binary TRUE again which prompts switch S3 **801** to open to halt the update equalizer's weights. At the same time that switch S3 **801** is opened, switch S5 **808** is closed and switch S6 **809** is opened to set the maximum count of the overflow counter **802** back to the value

given by P1 811. This process continues with the increment register 804 is again set to zero switch S3 801 controlling constraint update rate through switches S5 808 and S6 809, and parameters P1 811 and P2 812.

Referencing FIG. 5 again, after passing through ALG-6 521 the adjustment signal associated with the constraint error, and derived from ALG-5 508, is delivered to algorithm ALG-2 509 which performs an update of the contents of the equalizer's FF weight register bank 503, this time in accordance with the MF constraint criterion. ALG-2 509 refers to one of any number of algorithms that can control the adaptation of the equalizer's weights.

FIG. 4 illustrates a detailed block diagram of ALG-2 509 in accordance with a preferred embodiment of the present invention as previously described and discussed.

This completes the MF portion of the joint ISI-canceling and MF operation at the current iteration.

The entire joint process equalizer update is repeated for the next iteration beginning with the elements currently residing within the data register bank 501 being shifted to the right by one position and the next sample of the distorted input waveform being loaded into the first position of the data register bank 501. The ISI-cancellation process is initialized once again with closure of switch S1 502 and the computation the inner product between the contents of the data register bank 501 and the contents equalizer FF weight register bank 503.

We now discuss several possible configurations for ALG-ISI-ERR 507 of FIG. 5 which generates the error sequence that drives the update of the equalizer's weights in accordance with the criterion for the cancellation of ISI. ALG-ISI-ERR 507 pertains to any state-of-the-art algorithm that can derive an error signal pertaining to the cancellation of ISI.

FIG. 9 depicts a detailed block diagram of ALG-ISI-ERR 507 of FIG. 5 in accordance with a preferred embodiment of the present invention. This embodiment utilizes a training sequence

**901** to form the ISI error signal.

With respect to **FIG. 9**, after passing through the 2:1 commutator **506** (ref. **FIG. 5**) and switch **S1 502** (ref. **FIG. 5**) the equalized signal is subtracted from a known training sequence **901**, which represents samples of the distortion-less transmitted sequence at symbol rate, using a differencing node **902**. The difference signal represents the ISI error sequence and is passed to **ALG-1 508** (ref. **FIG. 5**) to generate the adjustment signal that directs the equalizer's weight in accordance with ISI cancellation.

**FIG. 10** depicts a detailed block diagram of **ALG-ISI-ERR 507** of **FIG. 5** in accordance with an alternate embodiment of the present invention.

With respect to **FIG. 10**, after passing through the 2:1 commutator **506** (ref. **FIG. 5**) and switch **S1 502** (ref. **FIG. 5**) the equalized signal is passed through a slicer (decision device) **1001** which quantizes the equalized signal to the closest 2-tuple of a decision region. A differencing node **1002** subtracts the pre-quantized sample from the quantized sample to form the error sequence which is then passed onto **ALG-1 508** (**FIG. 5**) to generate the equalizer weight adjustment signal. This embodiment is termed the decision-directed embodiment.

**Fig. 11** depicts a detailed block diagram of **ALG-ISI-ERR 507** of **FIG. 5** in accordance with an alternate embodiment of the present invention. In this embodiment the channel inversion error is formed via the use of a statistical-based update.

With respect to **FIG. 11**, an algorithm **ALG-7 1101** computes the value of a parameter  $R_m$  measuring a ratio of statistical moments of the original modulated signal. A switch **S7 1102** is closed to deliver the value of parameter  $R_m$  to a register **1103** where it will reside throughout the processing. Switch **S7 1102** is then opened. Therefore, **ALG-7 1101** executes only a single time to calculate  $R_m$  and then is removed from the processing when switch **S7 1102** is opened.

After passing through the 2:1 commutator **506** (ref. FIG. 5) and switch S1 **502** (ref. FIG. 5) the input sample of equalized signal is delivered to a complex conjugation device **1104**. The output of this complex conjugation device is then multiplied by the input sample of equalized signal using a multiplier device **1105**. The content of the register **1103** storing the value of parameter  $R_m$  is subtracted from this product via a differencing node **1106** and this difference is then multiplied by the input sample of equalized signal via a multiplier element **1107**. This last product represents a sample of the error sequence delivered to ALG-1 **508** (ref. FIG. 5) to form the weight adjustment signal as in previous embodiments.

The statistically based parameter  $R_m$  is the ratio of moments of the amplitudes  $a_j$  ( $j = 1, 2, \dots, B$ ) of the B-ary pre-pulse-shaped modulated constellation.

$$R_m = E[|a_j|^{2m}] / E[|a_j|^m] \quad [3]$$

ALG-7 **1101** refers to one of any number of algorithms that can compute the ratio of  $E[|a_j|^{2m}]$  to  $E[|a_j|^m]$  where the operator  $E[x]$  denotes the expectation of  $x$ .

Fig. 12 depicts a detailed block diagram of ALG-7 **1101** of FIG. 11 in accordance with a preferred embodiment of the present invention. The first amplitude  $a_1$  of the set of amplitudes  $a_j$  ( $j = 1, 2, \dots, B$ ) of the B-ary pre-pulse-shaped modulated constellation is passed through an absolute value operator **1201** to produce a value V1. A counter **1202** increments the value in a register **1203** from 0 to 1 with the use of a scalar **1204** set to the value of 1 and a summing node **1205**. A scalar **1206** set to the value of B and an overflow test **1207** test whether the contents in register **1203** have exceeded the value given by parameter B **1206**.

V1 is passed through a power operator **1208** which computes V1 to the  $m$ -th power with use of parameter  $m$  **1209**. The output V2 is then sent to two different paths of processing, an upper

and lower path. In the upper path V2 is passed through a squaring operation **1210** to form V3 which, in turn, is delivered to the combination of a summing node **1211** and a delay register **1212** to perform an accumulation of future V3 values. In the lower path V2 is delivered to the combination of a summing node **1213** and delay register **1214** to perform an accumulation of future V2 values. The entire process is repeated with input of the second 2-tuple  $a_2$ .

After all of the constellation 2-tuples have been processed the value in the increment register **1203** increments one more time. At this point, the value in the increment register **1203** exceeds the value given by parameter B **1206** and a CLOSE signal is sent to switches S8 **1215** and S9 **1216**. A division operator **1217** forms the ratio of the final values of V2 and V3 to form  $R_m$ .

**FIG. 13** depicts a detailed block diagram of an alternate embodiment of the present invention. This embodiment closely resembles decision-directed embodiment with the exception that a feedback signal formed from a weighted set of previous slicer decisions adds to the equalized signal. This embodiment of the present invention is termed the decision-feedback embodiment.

The process for the decision-feedback embodiment is as follows. With the output of the 2:1 commutator **506** (ref. **FIG. 5**) already formed and passed through switch S1 **502** (ref. **FIG. 5**), the contents of a decision register bank **1301**, which stores a set of the previous decisions produced from a slicer **1302**, engage the contents of a weight register bank **1303**, storing values of set of DF weights, in an inner product computation using a bank of multiplier elements **1304** and summing nodes **1305**. This inner product computation represents a sample of the DF's contribution to the total equalized signal.

Next, the incoming signal to the DF embodiment is added to the DF sample using a summation node **1306**. The result of the addition represents a sample of the equalized signal and is passed to the slicer device **1302**. The equalized sample is subtracted from decision produced



from the output of the slicer **1302** via a differencing node **1307** forming a sample of the ISI-cancellation error sequence. The error sample is then delivered to ALG-1 **508** (ref. **FIG. 5**) to form the adjustment signal needed to update the contents of the equalizer's FF weight register bank **501** (ref. **FIG. 5**).

The sample of adjustment signal formed from ALG-1 **508** then multiplies contents of the decision register bank **1301** using a bank of multiplier elements **1308**. The resulting bank of products then adds to the current contents of the DF weight register bank **1303** using a bank of summing nodes **1309**, and the result is stored in the DF weight register bank **1303**. As an example of the DF weight update, the contents of the first (far left) register of the decision register bank **1301**, storing a set of previous decisions, multiplies the adjustment signal produced from ALG-1 **508**. The product adds to the first (far left) register position of the DF weight register bank **1303** and the sum is stored in the first register position of the DF weight register bank **1303**. The update process continues with the next successive register positions of the DF weight register bank **1303**.

At the completion of DF weight update the contents of the decision register bank **1301** are shifted to the right by one register position. The slicer **1302** output is delivered to first register position of the decision register bank **1301**. The DF operation then repeats with the inner product of the decision register bank **1301** and the DF weight register bank **1303**.

With the description of the basic processing of the joint ISI-canceling and MF adaptive equalizer completed we now return to descriptions of both ALG-4 **512** and ALG-7 **522**.

ALG-4 **512** performs windowing of the constraint waveform produced from ALG-3 **511** at the current equalizer iteration. When the constraint waveform is sinusoidal in nature a windowing of the sinusoidal time series weights the non-causal and causal samples furthest from the midpoint of the total duty cycle with negligible amplitude (or zero amplitude depending upon

the selected window function) while emphasizing those samples nearest the duty cycle midpoint with greater importance. As a result, the samples of the windowed constraint waveform of negligible amplitude offer negligible contribution to the inner product between the equalizer FF weights and constraint waveform associated with the MF processing. Hence, the their multiply operations need not be performed and the inner product reduces to performing only the central-most multiply operations that will restore a measure of performance equivalent to that of the non-windowed constraint waveform.

**FIG. 14** illustrates a detailed block diagram of **ALG-4 512** in accordance with a preferred embodiment of the present invention. This embodiment performs windowing of the constraint waveform using a single window function. Samples of the constraint waveform produced from **ALG-3 511** (**ref. FIG. 5**) are passed to a multiplier bank **1401** which performs a point-by-point multiplication with contents of a register bank **1402** representing the window function. The resulting samples of windowed time series are then loaded into the constraint register bank **510** (**ref. FIG. 5**) and as the MF processing is initiated. However, in the inner product computation between the contents of the equalizer FF weight register bank **503** (**ref. FIG. 5**) and the contents of the constraint register bank **510** (**ref. FIG. 5**), only those central multiplications of the multiplier bank **504** (**ref. FIG. 5**) and central sums of the bank of summing nodes **505** (**ref. FIG. 5**) which correspond to the central samples of the windowed constraint waveform samples of non-zero or appreciable amplitudes are performed.

For the singular windowing waveform various types of window functions may suffice for truncating the constraint waveform time series. For example, an unweighted window contains a steep decay in its time series which *maximizes* the number of extreme causal and non-causal samples of the windowed waveform that are of zero or negligible amplitude. This, in turn, *minimizes* the number of central-most multiplications and sums that need be performed in the

inner product associated with the MF constraint. The drawback, however, is that windowing with an unweighted function maximizes the amount of spectral leakage induced from waveform time series truncation which diminishes the strength of the orthogonality between equalizer and constraint waveform.

To compensate, the window function selected may contain a gradual decay of its time response such as the Hann, Hamming, Kaiser, etc. windows. For these windows, however, the number of samples of the windowed waveform, which are of zero or negligible amplitude, may not result in an appreciable workload reduction of the MF constraint processing. Hence, the window waveform is formed from a composite of multiple windows to achieved desired time series truncation with minimal spectral leakage.

**FIG. 15** illustrates a detailed block diagram of **ALG-4 512** in accordance with an alternate embodiment of the present invention. This embodiment performs windowing of the constraint waveform using multiple window functions. Switch **S8 1501**, initially in a closed position, allows the entire set of samples of the constraint waveform produced from **ALG-3 511 (ref. FIG. 5)** to be loaded to a register bank **1502**. Switch **S8 1501** is then opened. Next, a bank of multiplier elements **1503** performs a point-by-point multiplication of the pre-windowed samples contained in register bank **1502** with samples of the first windowing function contained in a register bank **1504**. The bank of products is stored in register bank **1502**. Switch **S11 1508** remains in an open position until all windowing waveforms have been utilized. Switch **S12 1505** then moves to the windowing waveform #2 register bank **1506**. The bank of multiplier elements **1503** performs a point-by-point multiplication of the pre-windowed samples contained in register bank **1502** with samples of the second windowing function contained in register bank **1506**. The bank of products is stored in register bank **1502**. The process is repeated for all the windowing functions up to an including the last storing in windowing waveform #W register bank **1507**.

Then switch S11 **1508** is closed to send the final version of the samples of windowed constraint waveform to the constraint register bank **510** (ref. FIG. 5).

ALG-7 **522** is now discussed. Referencing FIG. 5, ALG-7 **522** performs an initialization of the contents of the equalizer FF weight register bank **503** with the coefficients of the RRC MF as a means to decrease the acquisition time needed to form the MF characteristics of the equalizer's composite inverse channel and MF function.

FIG. 16 illustrates a detailed block diagram of ALG-5 **522** in accordance with a preferred embodiment of the present invention. Prior to the contents of the data register bank being shifted to prepare for the first sample of the distorted waveform to be loaded into the first position of the data register bank **501** (ref. FIG. 5), switch S13 is closed to allow a coefficient set **1601** of the pre-FSE RRC MF, which spans the duration of the equalizer's FF weights, to be loaded into the register positions of the equalizer FF weight register bank **503** (ref. FIG. 5). Switch S12 **1602** is then opened to disconnect ALG-7 **522** (ref. FIG. 5) from the joint process equalizer update.

FIG. 17 depicts a detailed block diagram of the joint ISI-cancelling and MF adaptive equalized partitioned as a polyphase process in accordance with a preferred embodiment of the present invention. The 2:1 decimator (ref. FIG. 5), previously at the output of the equalizer, is embedded within the fractional-spaced equalizer via the Nobel Identity. As a result, the data register bank **502** (ref. FIG. 5) is partitioned into two sub-register banks,  $\underline{u}_0$  **1701** and  $\underline{u}_1$  **1702**, each of which is half the length of the original non-polyphase partitioned data register bank **502** (ref. FIG. 5). In a similar manner the equalizer weight register bank **503** (ref. FIG. 5) is partitioned into sub-register banks  $\underline{w}_0$  **1703** and  $\underline{w}_1$  **1704**, and the constraint register bank **510** (ref. FIG. 5) is partitioned into sub-register banks  $\underline{c}_0$  **1705** and  $\underline{c}_1$  **1706**.

The polyphase process of FIG 17 is as follows. The elements contained within the data sub-register bank  $\underline{u}_1$  **1702** are shifted to the right by one position. A sample of the distorted input

waveform is then delivered to the first register position of data sub-register bank  $\underline{u}_1$  **1702** via a 2:1 commutation device **COM\_1 1707**.

At time  $t_{-1}$ , a switch **S1 1708** is closed to allow the contents of the data sub-register bank  $\underline{u}_1$  **1702** to engage the contents of equalizer FF weight sub-register bank  $\underline{w}_1$  **1704**, storing half of the equalizer's weights, the odd indexed weights (or even indexed weights depending upon polyphase methodology), in an inner product computation using a bank of multiplier elements **1709** and a bank of summation nodes **1710**.

In this embodiment, the polyphase configuration of the present invention, the number of multiplier elements in the multiplier bank **1709** and number of summing nodes in the bank of summing nodes **1710** are both approximately half that of each of the non-polyphase configuration. The inner product computation represents half the total equalized decimated result at the current iteration, and with switch **S1 1708** closed the inner product is stored in a single delay element **1711** for future use. Switch **S14 1712**, currently in an open position, prevents the error sample associated with ISI cancellation from being formed until the second half of the total equalized decimated signal is computed.

Next, samples of the signal representing the constraint waveform are loaded into constraint sub-register banks  $\underline{c}_0$  **1705** and  $\underline{c}_1$  **1706** using algorithm **ALG-3 1728**, but as in the non-polyphase embodiment, can also be passed first to an optional algorithm **ALG-4 1729** when the constraint waveform is sinusoidal in nature to limit duty cycle as a means to reduce the computational complexity of the MF processing. **FIG. 6** illustrates a detailed block diagram of **ALG-3 1728** in accordance with a preferred embodiment of the present invention as previously described and discussed. **FIGS. 14-15** illustrate detailed block diagrams of **ALG-4 1729** in accordance with preferred embodiments of the present invention as previously described and discussed.

At time  $t_{-2}$ , shortly after time  $t_{-1}$  and prior to the input of the next distorted sample to be

processed, switch S1 1708 is opened and a second switch S2 1713 is closed to allow computation of a second inner product, this time between the contents of the constraint sub-register bank  $\underline{c}_1$  1706 and the contents of the equalizer FF weight sub-register bank  $\underline{w}_1$  1704. Again the bank of multiplier elements 1709 and bank of summing nodes 1710 are used in forming this inner product. This second inner product represents the first half the total contribution to the sample measuring the orthogonality between the equalizer's FF weights and the constraint waveform at the current iteration. With switch S2 1713 closed it is stored in a single delay element 1714 for future use. Switch S15 1715, currently in an open position, prevents the MF constraint error from being formed until the second half of the total contribution to the measure of orthogonality between the equalizer's FF weights and the constraint waveform is formed. Switch S2 1713 is then opened.

Next, commutator COM 1 1707 moves to the data sub-register bank  $\underline{u}_0$  1702, and a new sample of the distorted waveform is input to the first register position of data sub-register bank  $\underline{u}_1$  1702. A second commutator COM 2 1716 moves to data sub-register bank  $\underline{u}_0$  1701 and constraint sub-register bank  $\underline{c}_0$  1705, while a third commutator COM 3 1717 moves to the equalizer FF sub-register bank  $\underline{w}_0$  1703, with all commutator movements controlled by a clock 1718.

The elements contained within the data sub-register bank  $\underline{u}_0$  1701 are then shifted to the right by one position and the next sample of the distorted input waveform is then delivered to the first register position of data sub-register bank  $\underline{u}_0$  1701 via the commutation device COM\_1 1707.

At time  $t_{-3}$ , shortly after the input of the next distorted sample to data sub-register  $\underline{u}_0$  1701, switch S1 1708 is closed to allow the contents of the data sub-register bank  $\underline{u}_0$  1701 to engage the contents of equalizer FF weight sub-register bank  $\underline{w}_0$  1703 in a third inner product computation using the bank of multiplier elements 1709 and bank of summing nodes 1710. With switch S1

**1708** closed this third inner product is added to the first inner product currently stored in the delay register **1711** via a summing node **1719** to form a sum  $Ps1$ .  $Ps1$  represents a sample of the equalized signal at the current iteration.

Next, switch **S14 1712**, is closed to send sum  $Ps1$  to ALG-ISI-ERR **1720** to form the error associated with ISI-cancellation. **FIGS. 9-11** illustrate detailed block diagrams of ALG-ISI-ERR **1720** in accordance with preferred embodiments of the present invention as previously described and discussed.

The error is then sent to ALG-I **1721** to form the adjustment signal needed to update the equalizer's FF weights in accordance with the criterion for ISI cancellation. **FIG. 3** illustrates a detailed block diagram of ALG-I **1721** in accordance with a preferred embodiment of the present invention as previously described and discussed.

Continuing with the process description of **FIG. 17** the adjustment signal formed at the output of ALG-I **1721** is then passed to switch **S1 1708**. In this position, switch **S1 1708** permits an update of the contents of the equalizer's FF weights when the adjustment signal is derived from the channel inversion error and prevents the channel inversion error adjustment signal from updating the FF weights when the present invention switches its mode of operation to the MF processing. With switch **S1 1708** in a closed position, the adjustment signal derived from ALG-I **1721** is delivered to algorithm ALG-2 **1722** which performs an update of the contents of the equalizer FF weight sub-register banks  $w_0$  **1703** and an update of the contents in equalizer FF weight sub-register banks  $w_1$  **1704**. **FIG. 4** illustrates a detailed block diagram of ALG-2 **1722** in accordance with a preferred embodiment of the present invention as previously described and discussed.

This completes the weight update associated with the ISI-cancellation process at the current iteration for polyphase embodiment of the present invention.

At time  $t_4$ , shortly after time  $t_3$  and prior to the input of the next distorted sample to be processed, switch S1 **1708** is opened and switch S2 **1713** is closed to allow computation of an inner product, the fourth inner product in the series, between the contents of the constraint sub-register bank  $c_0$  **1705** and the contents of the equalizer FF weight sub-register bank  $w_0$  **1703** using the bank of multiplier elements **1709** and the bank of summing nodes **1710** servicing the computation. With switch S2 **1713** closed the fourth inner product is added to the second inner product currently stored in the delay register **1714** via a summing node **1723** to form a sum Ps2. Ps2 represents a sample of the total measure of orthogonality between the equalizer's FF weights and constraint waveform at the current iteration.

Next, switch S15 **1715** is closed to send sum Ps2 onto the processing that derives the constraint error. Ps2 is subtracted from the constraint level parameter  $\beta$  **1724** using differencing node **1725** as in the previous embodiments. The difference, termed the constraint error, is passed to an algorithm ALG-5 **1726**, as in prior embodiments, to form the adjustment signal needed to update the contents of both equalizer FF weight sub-register banks,  $w_0$  **1703** and  $w_1$  **1704**, in accordance with the MF constraint criterion.

With switch S2 **1713** closed the adjustment signal derived from the MF constraint error is passed to algorithm optional ALG-6 **1727** to control the rate at which the contents of equalizer FF weight sub-register banks  $w_0$  **1703** and  $w_1$  **1704** are to be updated in accordance with the MF constraint criterion. FIG. 8 illustrates a detailed block diagram of ALG-6 **1722** in accordance with a preferred embodiment of the present invention as previously described and discussed.

Continuing with the process description of FIG. 17, after passing through ALG-6 **1727** the adjustment signal associated with the constraint error, and derived from ALG-5 **1726**, is delivered to algorithm ALG-2 **1722**, as in previous embodiments, which performs an update of the contents of the both the equalizer FF weight sub-register banks  $w_0$  **1703** and  $w_1$  **1704** in



accordance with the MF constraint criterion. Switch S15 1715 is then opened.

This completes the MF portion of the joint ISI-cancelling and MF operation at the current iteration for the polyphase embodiment of the present invention.

Commutator COM\_1 1707 then moves back to the  $\underline{u}_1$  register bank 1702, COM\_2 1716 moves back to data sub-register bank  $\underline{u}_1$  1702 and constraint sub-register bank  $\underline{c}_1$  1706, and COM\_3 1717 moves back to the equalizer FF weight sub-register bank  $\underline{w}_1$  1704, all movements again controlled by the clock 1718. Also the contents of delay register 1711 and delay register 1714 are zeroed out.

The entire process is repeated with the contents equalizer data sub-register bank  $\underline{u}_1$  1702 shifted to the right by one position to prepare for the next sample of distorted input waveform to be delivered to the first register position of  $\underline{u}_1$  1702.

With respect to the configuration of ALG-ISI-ERR 1720 in the polyphase embodiment, FIGS. 9-11 illustrate detailed block diagrams of ALG-ISI-ERR 1720 in accordance with preferred embodiments of the present invention as previously described and discussed.

When ALG-ISI-ERR 1720 in the polyphase embodiment is defined as in FIG. 10, where a slicer forms the equalization error, a DF configuration can be used to enhance the cancellation of ISI. FIG. 12 illustrates a detailed block diagram of the DF configuration in accordance with a preferred embodiment of the present invention as previously described and discussed.

The polyphase embodiment of the present invention also benefits from initialization of the equalizer's FF weights using ALG-7 1730. FIG. 15 illustrates a detailed block diagram of ALG-7 1730 in accordance with a preferred embodiment of the present invention. Since the constraint register bank 510 (ref. FIG. 15) is partitioned into sub-register banks  $\underline{c}_0$  1705 and  $\underline{c}_1$  1706 in the polyphase embodiment, ALG-7 1730 initializes sub-register banks  $\underline{c}_0$  1705 and  $\underline{c}_1$  1706 with the odd and even indexed RRC MF taps, respectively, or vice versa.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims.